In-line extraction of rheological flow curves at constant production rate

Paolo Perona
Institute of Hydromechanics and Water Resources Management, ETH Zurich, 8093-Zurich, Switzerland

Sebastiano Sordo
Department of Hydraulics, Transports and Civil Infrastructures, Politecnico di Torino, 10129-Turin, Italy

A simple experimental technique to extracting the static rheological properties of manufacturing fluids at constant production rate is presented in this work. The method is based on the principle of the rectilinear pipe viscosimeter, and it is thought be inserted directly in the main production line. By means of a system of parallel pipes interconnected together with a convenient combination of butterfly valves (which are accordingly regulated to redistributing the flow) the flow curve can be built upward on one tube and downward on the other. A pilot experimental facility allowed to testing the feasibility of such an idea on some real food fluids (fruit purees both raw and 10% in volume diluted with water) showing a marked non-Newtonian behaviour. Additional experiments were also made, by varying the fluid temperature. The experiments made up on different pipe diameters confirmed the absence of anomalous flow conditions and, in turn, the reliability of the results. These latter are encouraging and show the usefulness of this technique, which could be easily coupled with the recent UVPPD method so to obtain real time monitoring. Additional experiments aiming at automating the whole process, as well as testing this system on a real production line are foreseen.

Keywords: In-line rheometry, capillary viscosimeter, food fluids, fruit purees, non-Newtonian fluids.

1 INTRODUCTION

Research and development are important strategic sectors for supporting the continuous establishment of both new production and quality control techniques. For food industries, for instance, the need of a permanent improving in the manufacturing techniques meets essentially with the ever more demanding requests of customers. Methods for controlling the products quality along all the productive cycle play therefore a key role in order to guarantee that the final result has the foreseen organoleptic, chemical and physical properties. In industrial plants for continuous production, a rather common procedure is to periodically spill out a given volume of material in some point of the production line (or even in more than only one, actually), and to perform the analyses foreseen by the quality and health standards. Among the classical standard measurements there are bulk density, Bostwick consistency, Brix and acidity content, pH degree, etc. These quantities are good indicators that have been long used for their relative quick and economic measurement practice. However, in some cases a more detailed rheological analysis would help to better understanding the product fluid dynamical behaviour within some specific mechanical devices or geometries. Several studies have more or less successfully tried to correlate the aforementioned quantities together with the rheological properties. Such efforts are in some cases meaningful and, therefore, they represent a not negligible time and cost saving. Hence, an immediate further step would be the implementation of the rheological measurements directly in-line with the production plant. Such a goal has now been long pursued by researchers and some remarkable achievements were reached [1,2]. The optimum is obtained when the rheological information (or some other quantity of particular interest) can be obtained quickly, in aseptic conditions, and without disturbing the productivity of the plant too much. Although sometimes uncertainty still accompanies results pursuing high-level of details, the techniques that have been proposed in literature so far [2], represent the outstanding direction leading the future research in this field.

The method proposed in the following is conceptually simple and economically convenient and allows to obtaining the rheological flow curve within a reasonable time span. Its functioning is based on the rectilinear pipe viscosimeter and, as such, can be easily inserted in series with the production line. Moreover, it assures that the rheological information is obtained without varying the production rate of the whole industrial plant. At present such a technique is still at a prototype level, but its implementation to a real case is straightforward.

2 METHOD, DEVICE AND EXPERIMENTS

2.1 Outlines of the method

Let us consider an industrial production plant where a given product is formed throughout a series of processes and, eventually, delivered to some storage reservoir. This picture is very likely the one that characterizes industrial plants devoted to the production of purees (both fruits and vegetables), tomato sauces and, why not, also melt chocolate. Obtaining a flow curve on such production lines would be possible by using the classic technique of

the rectilinear pipe viscosimeter. That is, by varying the flow rate and simultaneously sampling the pressure drop over a fixed reach length. Data of flow rate and differential pressure should then be transformed into wall shear stress and wall shear rate, and by applying the common Rabinowitch and Mooney correction (see later on the paragraph). However, this technique would compromise the continuous production of the industrial plant. In facts, a discrete range of flow rates between zero and the maximum should be covered in order to obtain the complete rheological information. The whole situation can be improved as follows.

With reference to Figure 1 let the main production line be indicated by the broad segment and having pipe diameter D_m. Suppose to install on such a line two T- junctions in the points A and B, respectively. A by-pass tube of diameter D_b between such two points can then be connected and regulated by means of two automatic servo-controlled valves V_1 and V_2. An electromagnetic flow meter M can then also be mounted on the main line after the valve V_1. Two groups of pressure transducers (P_1, P_2, P_3) and (P_4, P_5, P_6) are then installed as sketched in Figure 1. The distance between the transducers of each battery must be equal to a fixed known value d_m, d_b. Under steady motion conditions and in the absence of disturbing effects, the pressure drop between the first and the second transducers is equal to that measured by the second and the third one,

$$\Delta P_1 = P_1 - P_2 \cong \Delta P_2 = P_2 - P_3$$
$$\Delta P_3 = P_4 - P_5 \cong \Delta P_4 = P_5 - P_6 \qquad (1)$$

These conditions satisfied imply that a correct pressure drop measurement is currently being done, whereas any discrepancy could be due to excessive secondary currents (i.e., transducers too close to some disturbing geometry such bends, flow meter, valves, etc.), non stationary flow conditions, wall slip, etc.

Starting from a flow on the main line corresponding to the foreseen production rate (indicated by M), then valves V_1 and V_2 are completely open and close, respectively. Suppose now that at the time t_0 a check of the rheological properties must be done.

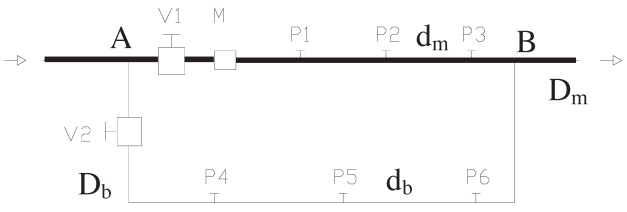


Figure 1: Sketch of the by-pass system that has to be connected in parallel with the production line. The broad reach indicates the main line, while the thin tract shows the bypass.

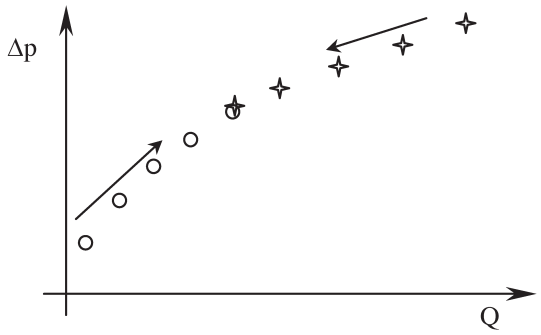


Figure 2: Sketch of the case with equal pipe diameters D_m=D_b and distance d_m=d_b among the pressure transducers. While opening V_2 the flow rate on the bypass tube increases and so does the pressure drop (o); the opposite happens on the main line (◊). When the valve V_2 is completely open the pressure drops on the two pipes will nearly be the same.

Then the valve V_2 can be gradually opened, thus allowing a certain flow to occur on the by pass. The difference between the production rate and the current reading of M will give the quantity that is being by-passed. The corresponding pressure drop can then be measured soon after the depletion of the transitory, the latter being indicated by the new steady value measured by the transducers. After having recorded the instruments reading for a time lapse then the procedure is repeated by gradually opening the valve V_2. Figure 2 shows a hypothetical scenario of how the measured pressure drops on both the pipes would change while implementing the procedure. Of course, pipe diameters as well as distances between the transducers can be different; in such cases the two curves will not match anymore in the state plane (Q, Δp). In the absence of anomalous flow effects such as wall slip, relevant elastic properties or pronounced hysteretic phenomena then, such a scale effect should disappear as soon as the flow curves are extracted from the measured data.

The processing of viscosimetry data to obtain the rheological flow curve starts from the measurements of flow rate Q and differential pressure Δp in laminar steady motion conditions. From such quantities the wall shear stress τ_w and the apparent wall shear rate $\dot{\gamma}_a$ can be immediately calculated as

$$\tau_w = \rho g \frac{DL}{4\Delta p} \quad ; \qquad \dot{\gamma}_a = \frac{8u_m}{D}. \qquad (2)$$

Here ρ is the fluid density, g is gravity, D the pipe diameter that is being considered, u_m the mean flow velocity and L the length of the reach over which the pressure drop Δp is measured.

The apparent wall shear rate can be numerically modified into the true one, by using the so-called Rabinowitsch and Mooney transformation, i.e.

$$\dot{\gamma}_w = \frac{8u_m}{D}\left(\frac{3n'+1}{4n'}\right); \qquad n' = \frac{d\left[\ln\left(\frac{8u_m}{D}\right)\right]}{d\left[\ln\left(\frac{D\Delta p}{4L}\right)\right]}, \tag{3}$$

which details can be found elsewhere [3,4]. This procedure can be easily implemented in an automatic fashion on both the pipes, so to obtain the rheological behaviour of the fluid as an output of the methodology discussed so far.

2.2 Laboratory device

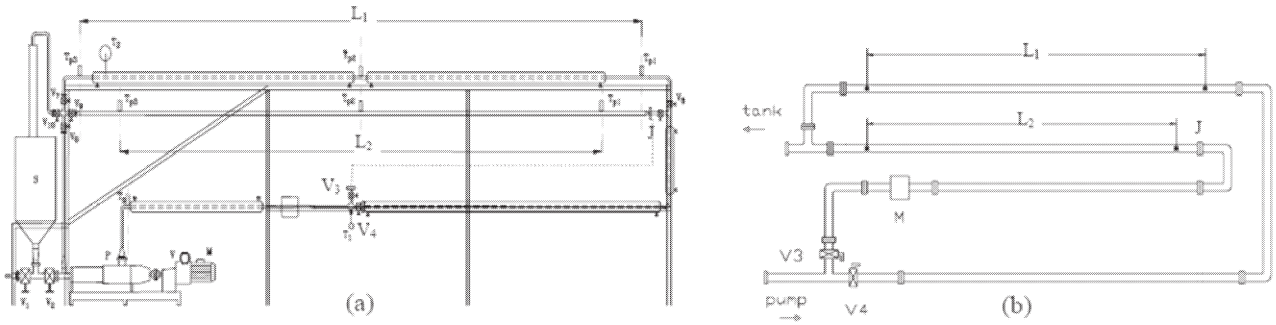
This technique was implemented at a laboratory scale on the experimental loop already used by [XX] and shown in Figure 3. This is an experimental facility with thermal control that was designed and used either as a rectilinear pipe rheometer or as a flow loop [4]. The flow loop was carefully designed to ensure steady simple shear flow across the entire measuring zone. The volumetric positive-displacement screw pump (P) is connected to an electric motor (M) via a mechanical speed control gearbox (V). In this way a continuous range of apparent shear rates $\dot{\gamma}_a$ from 0 up to 1400 s^{-1}, can be achieved. The pressure drop was measured across a reach L1 (7 m) of an approximately 9 meters long straight pipe with an internal diameter D of 0.025 m. The pressure was measured using three membrane pressure transducers P1, P2, P3 (WIKA TRONIC LINE), while the flow rate Q and the fluid temperature T were controlled by an electromagnetic flow meter and a couple of thermocouple sensors respectively connected to a LabView (National Instruments) commercial hardware and software system (see also Perona (2000) for further details). For our specific purposes the pump speed was set equal to the maximum, so to simulate the constant production rate of industrial plants. Moreover, the system of valves was manually regulated. Each valve covered a discrete range of seven different apertures degree, thus allowing to sampling the rheological curve over 14 points. While on one pipe the flow curve was built for increasing flow rate, measurements for decreasing flow rate were also done on the other pipe. Experiments with either equal or different pipe diameters were also done, so to check against the presence of anomalous flow effects and hysteresis phenomena.

2.3 Products being tested

Experiments were made on samples of both pear and peach puree that were produced by the Allione Industrie Alimentari in the year 2001 and then stocked into aseptic containers at constant temperature of 0°C. Such products are the result of the first industrial treatment on raw fruits. They typically show a two-phase structure, which is characterized by a liquid matrix with a high content of pulp. This latter, confers the fluids natural high both consistency (Bostwick) and Brix degree (i.e., sugar content) characteristics. Moreover, they show sensible internal destructuration when subjected to high mechanical stresses, as well as a relevant tendency to oxidation if not stored within protected atmospheric environments [3]. These products are typically used either for baby food production or as fruit juices after a certain dilution with water or syrup is done. An initial volume of 30 l of fresh product was used for the measurements at 0% of dilution and at different temperatures (30, 35, 40 °C). Afterwards, the initial volumes of both the samples were diluted at a 10% percentage in volume of water, and measurements were done at a temperature of 30°C. In particular, such temperatures were chosen in order to reproduce the conditions actually existing on some reaches of the real production plant, which afterward could have reasonably host the prototype device.

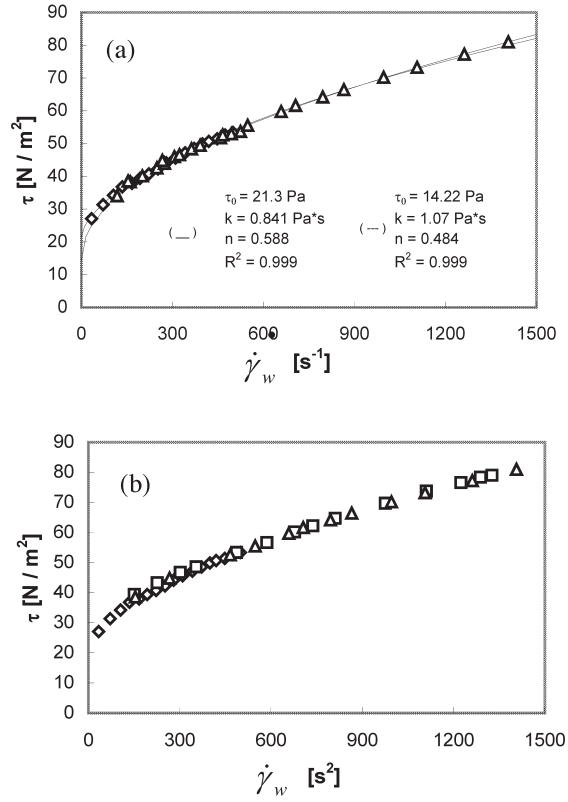
3 RESULTS

Although the manual regulation of the valves required some attention, all the experiments proved the feasibility of such a technique. Results were satisfactory for all the samples being investigated. Some examples are shown hereafter in Figures 4 and 5. A preliminary determination of the rheological flow curve was made using a single pipe of 36.5 mm diameter, and the technique documented in [3,4]. This operation served to first obtain a reference rheological curve, against which comparing those obtained with the proposed technique. No relevant differences were evident even when pipes with

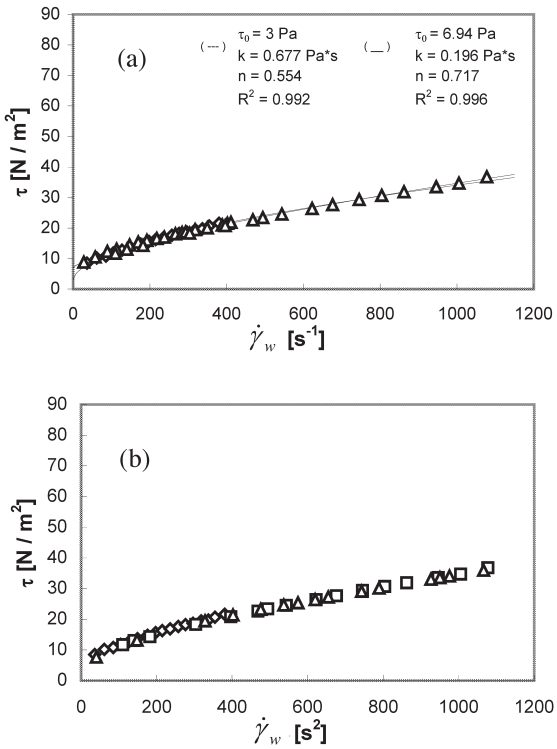


Figures 3. (a) Experimental loop already used by [XX] and (b) detail of the modification that was made in order to test the feasibility of the proposed methodology. A new tube reach (dotted line) was connected to the valve V_3 and the junction J.

different diameters were used. In principle, this is an important and crucial point, which guarantee that the results obtained on the pilot plant can be transferred to the production line scale. In Figures 4 and 5 results for the pear and peach purees at 30°C are respectively shown as static rheological behaviour on the plane (τ_w, $\dot{\gamma}_w$). Figures 4-5a show the flow curve built up using two different pipe diameters, whose data were corrected by means the Rabinowitsch–Mooney technique. Both the data measured on the by-pass (i.e., increasing flow) and the main line (i.e., decreasing flow), eventually matched together, and did not show any evident signs of possible anomalous flow behaviour. The same can be said for data in Figures 4-5b, wherein both the bypass and the main line had the same pipe diameter. In this latter case, however, the appearance of a weak hysteretic phenomenon for the pear puree was evident at low shear rates. The two curves seemed to not perfectly match together, thus making difficult the estimation of the yield stress value from simple data extrapolation. Such an hysteretic effect was observed to be temperature dependent, i.e. in general becoming worst when such a variable increased. On the contrary, dilution seemed to not particularly influencing the quality of the results.



Figures 4. Rheological flow curve of the fresh pear puree at 30°C. Comparison with the original flow curve (◇) and those measured with the proposed techniques. (a) upward and downward (△) measurement on a 25 and 36.5 mm pipe diameter; (b) upward (□) and downward (△) measurements on the same pipe diameter of 25 mm.



Figures 5. Rheological flow curve of the fresh peach puree at 30°C. Comparison with the original flow curve (◇) and those measured with the proposed techniques. (a) upward and downward (△) measurement on a 25 and 36.5 mm pipe diameter; (b) upward (□) and downward (△) measurements on the same pipe diameter of 25 mm.

4 CONCLUSIONS

A simple technique for extracting the rheological static information directly in-line and at constant production rate has been proposed in this work. Measurements on two different fluids have proven to be feasible and relatively quickly to obtain, provided that the strategy of measuring on both the main line and the bypass tube is adopted. In this way the curve can be built by varying the aperture of the valves (flow rates) only partially, and a complete measure requires time scales of the order of 10'. Since the principle of such a technique is that of the rectilinear pipe viscosimeter, this method can be straightforward coupled with other more modern and sophisticated techniques such as the UVP-PD one.

REFERENCES

[1] Barnes, H.: On-line or process viscometry: a review, Appl. Rheol. 9,3, (1999) 102-107.
[2] Ouriev, B.: Ultrasound Doppler based in-line rheometry of highly concentrate suspensions, ETH Ph.D. Dissertation No. 13523 (2000).
[3] Perona, P.: Rheology and fluid dynamics of fruit purees in circular pipes, Ph.D. Diss. XIII° ciclo, Politecnico di Milano (2001).
[4] Perona, P.: An experimental investigation of laminar-turbulent transition in complex fluids, J. Foog Eng. 60 (2003) 137-145.